An Application of Phase Change Technology in a Greenhouse[1]

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Abstract: This research paper focuses on the greenhouse that needs additional heat at night to insure an inside air temperature above 20℃, and applies a new type of shape-stabilized phase change material (PCM) composite wallboard to the inner surface of the north wall of the greenhouse. Through establishing the model of phase change greenhouse basing on the theory of phase change heat transfer, we research the influence of solar radiation and environment temperature on the heat transfer process in the greenhouse. We optimize the phase change temperature and enthalpy of PCM, and research the energy-saving characteristics of the greenhouses that adopt PCM wallboards during the winter season. The results show that when the phase change temperature of PCM is 26℃, the enthalpy is 60kJ/kg and the mix ratio is 40%. The energy conservation rate of the greenhouse can reach 20% during the winter.

Keywords: PCM; greenhouse; simulation computing, energy saving

Nomenclature Symbols:

c	specific heat（kJ/kg℃）
F	area（m^2）
h	convective heat conductivity（W/m^2℃）
H	enthalpy （kJ/kg）
I	irradiation （W/m^2）
k	heat transfer coefficient（W/m^2℃）
K	gas absorbance
Q	convective heat exchange（W）
QR	radiation heat exchange（W）
T	temperature（℃）
V	volume（m^3）
x	computed grid (cm)
X	angle coefficient

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Greek symbols:

α	thermal diffusivity（m^2/min）
β	transmissivity
γ	absorptivity
ρ	density（kg/m^3）
λ	thermal conductance（W/m℃）
ε	emissivity
σ	Stefan-Boltzmann constant
τ	time（min）

Subscripts:

a	air in green house
en	environment
east	east
fil	film
gro	ground
insu	inner surface
l	liquid state
m	PCM material
north	north
osu	outside surface
sun	sun radiation
s	solid state
south	south
west	west
veg	vegetable/plant
ven	air infiltration
wal	wall

1. INTRODUCTION

In the past two decades, solar agricultural greenhouses have been widely used in the northern area of China. They could provide and improve the growing conditions for vegetables, fruits or flowers in cold climates, thus increase plant quality and productivity and make full use of the northern soil. Although the winter sunlight ratio and the intensity of solar radiation are correspondingly higher in the north of China, the temperature is mostly below 0℃. In the mean time, the construction of traditional greenhouse is simple and rough, the heat insulating and storing capabilities of enclosures are relatively poor, so it can't satisfy the growing demand of vegetables or flowers only relying on the solar radiation, thus most of greenhouses must consume fossil fuels for heating, leading to high energy consumption. According to the survey in Beijing DaXing district , a traditional greenhouse (about 270 ㎡) costs about 13t coal annually. It not only consume massive non-renewable energy resources, but also release a great deal of greenhouse gases (CO、CO_2) in the burning process and pollute the environment. At the same time due to the bad ability of temperature self-control, when the environment temperature is between 0℃～8℃ the inside air temperature could reach 35℃, which is about 10℃ higher than the suitable growth temperature. So we must release this part of redundant heat from greenhouse in daytime, bringing on the energy waste again.

For an attempt to conserve energy and reduce dependency on fossil fuels, it has become necessary to seek effective means of reducing heating consumption and to shift portions of energy from daytime to night. The phase change material (PCM) can achieve this purpose. The most frequently used PCM for these purposes is $CaCl_2{\cdot}6H_2O$, which is a cheap material with the phase change temperature of 29.8°C and has fairly high enthalpy, about150 kJ/kg. But supercooling and sensitivity towards moisture are two serious disadvantages in the long-term using of the storage unit with $CaCl_2{\cdot}6H_2O$[1]. So our research team is researching on a new type of composite PCM wallboard, whose main components are paraffin and other traditional construction materials. This new shape-stabilized PCM undergoes reversible solid–solid phase change process in macrostructure and can be mixed up with common building materials such as gypsum. Basing on the temperature requirement of greenhouse, cover the inner facade of the north wall with this new PCM wallboard, which could absorb redundant solar energy in daytime and release it at night, finally realize the aim of energy conservation.

2. MATHEMATICS AND PHYSICS MODEL

2.1 Research Object

A physics model is set up, as shown in Fig1, basing on the investigative greenhouse in Beijing DaXing district. The model faces south and whose dimension is 43m×6.3m×3m. Table 1 shows the main thermal parameters of the outer enclosure. Some vegetables are planted in the greenhouse, where the growing temperature needs above 20℃ all day. And ground temperature must reach 15℃ in order to guarantee the survival of seedling. Air exchange frequency is considered 1 time per hour. Breath heat of vegetables and absorptivity of air should be also considered, owing to the effect of plants and high humidity.

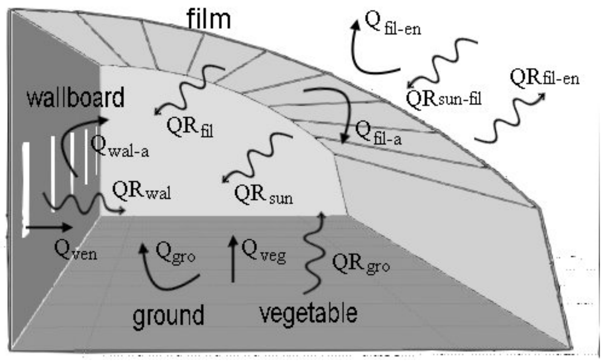

Fig. 1 The model of greenhouse

2.2 Heat Balance in Greenhouse

Actually heat transfer in the greenhouse includes several processes as follows[2][3]: the heat and mass transfer in soil; the heat and mass transfer among inside air, plants and enclosures; the heat radiation between plants and enclosures, and so on. All these processes not only depend on the complicated structure of greenhouse, the kind of plants, the optical trait of film and the component of wall, but also can be affected by random weather conditions. To simplify mathematic models, some basic assumptions are made as follows: ①the temperature of inside air is regarded as homogeneous and the effect of airflow is ignored; ②ground, film and wallboards are regarded as homogeneous and isotropic medium; ③ the vapor and breathing heat of plants are considered as constant and the mass transfer in greenhouse is ignored; ④the film cover with low heat capacity is computed as steady heat conduction; ⑤as the surface temperature of ground can reach 15 ℃ through paving ground film and horizontal radiation in greenhouse is almost absorbed by plants, the soil temperature varies slightly and can be considered as constant. Basing on above assumptions, we could analyze the distribution of energy in greenhouse and energy balance equations of air in greenhouse could be set up[4][5].

Tab. 1 The main parameter of the building materials

Component	Constitute material	Thickness mm	λ W/(m•K)	c kJ/(kg•K)	ρ kg/m^3
Outer Wallboard	1. concrete grout	20	0.93	0.837	1800
	2. brick	490	0.814	0.879	1800
	3. concrete grout	20	0.93	0.837	1800
Film	1. heat insulating layer	—	2.85	—	—
	2. PVC(film)		6.75		

$$\rho_a c_a V_a \frac{dT_a}{d\tau} = Q_{fil-a} + \sum Q_{wal-a} + Q_{gro-a} + Q_{veg} + Q_{ven} + QR_{sun-a} + \sum QR_{wal-a} \qquad (1)$$

As the thermal capacity of plastic film in greenhouse is very small, the heat transfer problem of plastic film could be calculated by the method of steady heat conduction; For soil heat transfer in greenhouse, the cultivation of plants in the surface of soil allows that most of sun light is absorbed by plants, and the soil temperature could be considered as steady all the day, so the heat transfer problem of soil could be calculated by the method of constant wall temperature; For other wallboards, the balance equation of heat transfer is:

$$\rho_{wal} c_{wal} V_{wal} \frac{dT_{wal}}{d\tau} = QR_{sun-wal} + Q_{wal-en} + Q_{wal-a} + \sum QR_{wal-wal} \qquad (2)$$

2.3 Mathematics Model

2.3.1 Instability Heat Transfer in the Wallboard

The heat transfer in the wallboard is calculated by the finite differential method. Considering the thickness is far less than the length and the height, the heat transfer in the wallboard could be regarded as one dimension process. The conductive differential equation of the inner temperature distribution in the wallboard, the Fourier laws parse equation and boundary conditions of equation are drawn as:

$$\frac{\partial T}{\partial \tau} = a \frac{\partial^2 T}{\partial x^2} \qquad 0 \le x \le L \qquad (3)$$

$$q = -\lambda \frac{\partial T}{\partial x} \qquad 0 \le x \le L \qquad (4)$$

$$-\lambda \left.\frac{\partial T_{wall}}{\partial x}\right|_{x=0} = h_{insu}\left(T_{insu} - T_a\right) + Q_{wrad} \qquad (5)$$

$$-\lambda \left.\frac{\partial T_{wall}}{\partial x}\right|_{x=L} = h_{osu}\left(T_{osu} - T_{en}\right) + \gamma_{wall} I \qquad (6)$$

Equation（3）is dispersed and solved by Gauss-Seidel type iterative method. Use intermediate differential format in space, and unit length is 1cm. For convergence, use whole hidden differential format in the time, and time step is 1min.

2.3.2 Radiation Absorbed by Inner Surface of Wallboard

Because there are abundance of vapor and CO_2 in the greenhouse, the solar radiation emitting on the greenhouse could be partly absorbed by the greenhouse gas. And due to the shading and high absorbance of plants, which is about 0.92, the reflection between soil and enclosures can be ignored[6]. At the same time, the reflection of irradiation between other wallboards is only calculated 1 time. So the equation of radiation absorbed by inner surface of wall is (7).

2.3.3 Heat Transfer Process in the PCM Wallboard

The analyses methods of PCM wallboard and common wallboard are similar, but phase change phenomena in this PCM wallboard under different temperatures should be considered. Here we solve the problem of phase change by the sensible heat capacity method[7]. The latent heat of phase change

$$Q_{wrad} = \gamma_{wall} \cdot \beta_{film} \cdot K \cdot \left(I + \sum_{i=1}^{2} (1-\gamma_{wall}) \cdot I \cdot X_i \right) + \sum_{i=1}^{2} \frac{\sigma \left(T_{insu}^4 - T_i^4 \right) X_i}{(1/\varepsilon_{insu}) + (1/\varepsilon_i) - 1} \quad (7)$$

is regarded as a large sensible heat capacity during a certain range of phase change temperature. So this problem can be transformed to a heat conduction problem of non-linear single phase, which could be expressed as:

$$C^* = \begin{cases} C_s(T) & T < T_m - \Delta T \\ \dfrac{\rho \mathrm{H}}{2\Delta T} + \dfrac{C_s + C_l}{2} & T_f - \Delta T \le T \le T_m + \Delta T \\ C_l(T) & T > T_m + \Delta T \end{cases} \quad (8)$$

As the researched PCM behaves a new kind of solid-solid material when it experiences phase change process, the thermal conductance is regarded as constant.

Basing on the mathematics models above, energy balance of greenhouse can be completely described. Introduce the equations (3)-(8) to the energy balance equations(1),(2), compile the program by Matlab software and we can get the final results. The framework of program is shown in Fig.2.

$$\begin{aligned} \rho_a c_a V_a \frac{dT_a}{d\tau} = {} & k_{fil} \left(T_{en}^{\tau} - T_a^{\tau} \right) F_{fil} + \sum h_{insu} \left(T_{insu}^{\tau} - T_a^{\tau} \right) F_{wal} + k_{gro} \left(T_{gro}^{\tau} - T_a^{\tau} \right) F_{gro} \\ & + Q_{veg}^{\tau} + V_{ven}^{\tau} c_{en} \rho_{en} \left(T_{en}^{\tau} - T_a^{\tau} \right) + I^{\tau} \beta_{fil} \gamma_a F_{fil} + \sum QR_{wal}^{\tau} \gamma_a \end{aligned} \quad (9)$$

$$\rho_{wal} c_{wal} V_{wal} \frac{dT_{wal}}{d\tau} = \gamma_{wal} I^{\tau} + h_{osu} \left(T_{en}^{\tau} - T_{osu}^{\tau} \right) + h_{insu} \left(T_{insu}^{\tau} - T_a^{\tau} \right) + \sum QR_{wal}^{\tau} \quad (10)$$

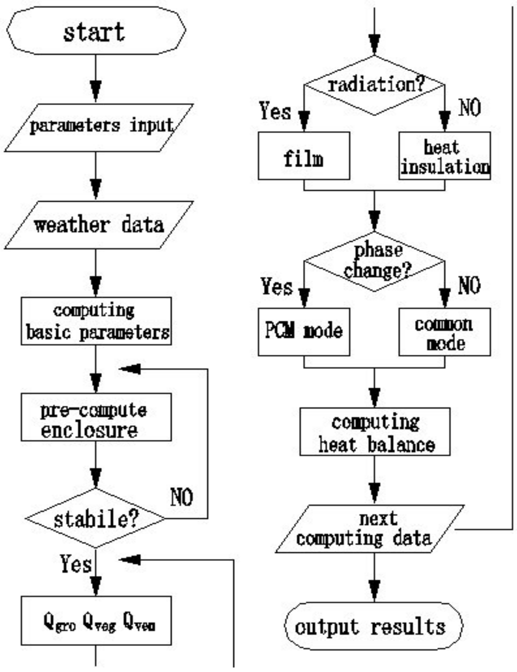

Fig. 2 The framework of program

3. RESULTS AND DISCUSSION

Choose typical weather data in Beijing (1.11~1.15) and calculate basing on the traditional greenhouse. From the curve of air temperature in greenhouse (Fig.3a), we could get some conclusions: ①solar radiation is attainable and abundant in the 5 simulating days. The minimum southern solar radiation appears at 12:00 in the second day, which is 550W/㎡; And the maximum south solar radiation appears at the fifth day, which is as high as 810 W/㎡ at 12:00. Though the average outside temperature is only -5℃, due to solar radiation the inside air temperature in greenhouse can reach 30℃ in the daytime. So the inside air temperature is mainly influenced by the outside solar radiation. ②Because the south solar radiation is higher than the east and west, the radiation absorbed by the inner north wallboard is higher than the east and west, the inner surface temperature of north wall is 1℃ higher than the east and west wallboard. ③Due to covering heat insulation layer on the plastic film, the inside air temperature drops very slowly at night.

The enclosure of the traditional greenhouse is usually very massive in order to increase the heat store capacity of wallboards. As figure 3b shows, although the outer surface of wallboard is covered with heat insulating layer, it couldn't increase the inner surface temperature of wallboard or decrease the fluctuation of temperature. As to the character of high temperature in the daytime and abundant solar radiation in the greenhouse, absorb this superfluous heat energy by the PCM, increase the inner surface temperature of the wall, and release it at night when the inside air temperature decreases. Follow this way we can the energy saving aim.

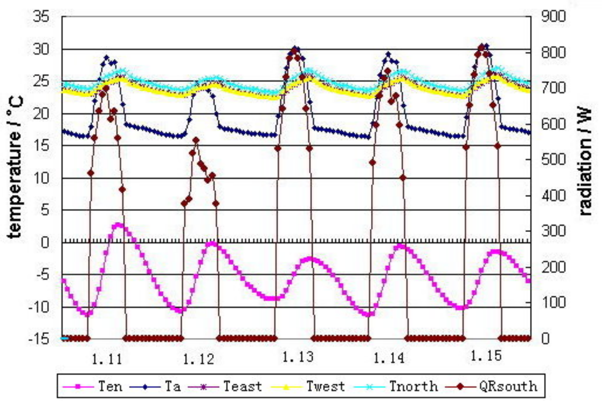

Fig. 3a The temperature of traditional greenhouse

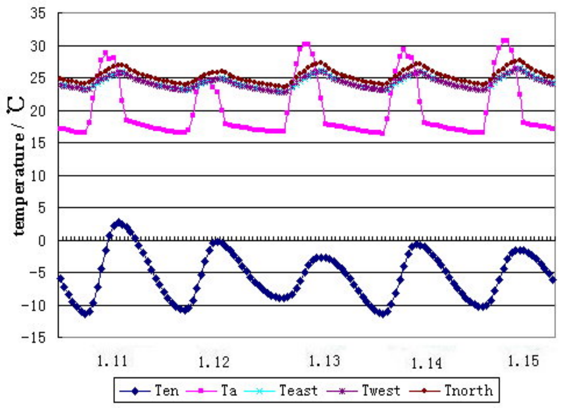

Fig. 3b The temperature of greenhouse with heat insulating layer

4. USE OF PCM

As the PCM can increase the heat capacity of wallboard and make light wallboard have the thermal characters of the heavy wallboard in certain temperature range, in order to emphasize the traits of PCM, reduce the thickness of greenhouse wall from 490mm to 240mm. And add the new composite PCM wallboard, whose color is deep black (Fig.4), to the inner surface of wall. This research wants to study the influence of the phase change temperature, the phase change enthalpy and the mix ratio on the energy consumption of greenhouse in winter by the simulating method.

4.1 The Phase Change Temperature

Add the 40mm PCM wallboard to the inner surface of north wall, change the phase change temperature, and research the effect of phase change technology to the energy efficiency of greenhouse in the condition of typical day of Beijing from Jan.1to Jan.5. From Fig.5 we can find that in traditional greenhouse the everyday fluctuation of north wallboard surface temperature is about 4℃ and the average temperature is 24.8℃ during the 5 days; After adding PCM to the north wallboard and with the increase in the phase change temperature of PCM (from25℃ to 29℃), the surface temperature of the wallboard rises and the daily variation becomes smoothly.

Fig. 4 The picture of new composite PCM

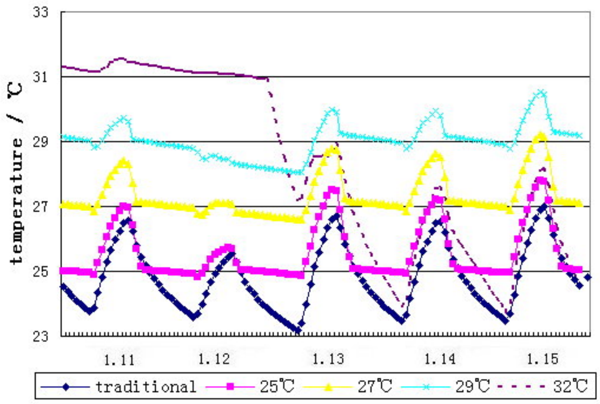

Fig. 5 The surface temperature of north wallboard in different phase change temperature

When the solar energy is adequately absorbed by PCM in sunny day, redundant solar energy can heat up the inner surface temperature of wallboard, and PCM with high phase change temperature can store more energy. At night as the great temperature difference between PCM with high phase change temperature and inside air, the more heat releases from PCM and the wallboard surface temperature drops obviously, such as the curve of 29℃. So in a certain temperature range the PCM with high phase change temperature is much more benefit for energy conservation of greenhouse. Such as shown in Fig.6, comparing 23℃ PCM, 31℃ PCM could save 25% energy in 5 days. But if the phase change temperature of PCM is chosen too high or unreasonable, the PCM cannot store enough solar energy in cloudy day or low sun radiation day and cannot continuously release heat at night. As the curve of 32℃ in Fig.5 shows, because of the weak radiation in the second day, the solar energy absorbed by PCM unable to satisfy the heat load at night, at the same time the temperature of PCM dropped quickly in the third day and couldn't reach the phase change temperature in the next days, the effect of PCM is useless. So the selection of melting temperature of PCM should be considered average variation of annual inside air temperature.

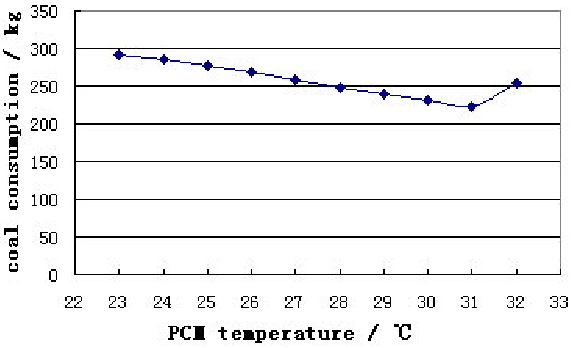

Fig. 6 The curve of coal consumption in 5 days

Generally speaking, choose the average of room design temperature and maximum temperature of greenhouse as the ideal phase change temperature of PCM. As shown in Fia.3a, the maximum temperature of greenhouse is about 31℃ and room design temperature is 20℃, so the best phase change temperature is 26℃. And through the Differential Scanning Calorimetry (DSC) test to evaluate the thermal performance of this new shape-stabilized PCM, as shown in Fig.7, we find that ,when the phase change temperature is near 26℃, the heat flow is about 151.2 mJ/mg, which is about 180 times higher than the common wall.

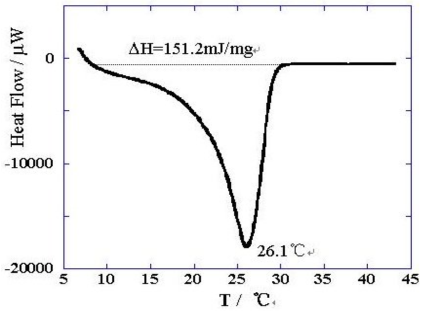

Fig. 7 The DSC curve of new composite PCM

4.2 The Latent Heat and the Mix Ratio of PCM in Wallboard

The larger latent heat of PCM is, the large thermal storage capacity of wallboard will be; Similarly, the higher mix ratio of PCM in wallboard is, the greater thermal storage capacity will be.

As show in Fig8, when the phase change temperature of PCM is 26℃, and other calculation conditions are the same to the section 2. When the latent heat of PCM wallboard is increased from 30kJ/kg to 150kJ/kg, the inner surface temperature of wallboard increases in the daytime while the fluctuation of surface temperature diminishes accordingly at night, which is benefit to the energy saving of greenhouse.

The experiment results of this research show that the optimal ratio of PCM in basic building materials is about 40%, the latent heat is about 60kJ/kg, and the PCM wallboard also can reach the intensity request of structure.

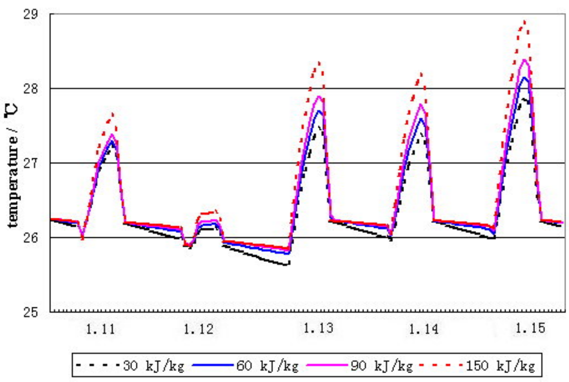

Fig. 8 The surface temperature of north wallboard in different enthalpy

4.3 Analyses of Heating Energy Consumption in Winter

For the sake of further analyses of energy efficiency in greenhouse in which phase change technology is used, simulate and compare the heating energy consumption and variation of inside air temperature between traditional greenhouse (490mm brick) and PCM greenhouse (200mm brick + 50mm PCM wallboard) in the whole winter.

Simulation time: 11.1~3.20, 140 days together; Simulation conditions: the phase change temperature of PCM is 26℃, the ratio is 40%, and the latent heat is 60kJ/kg.

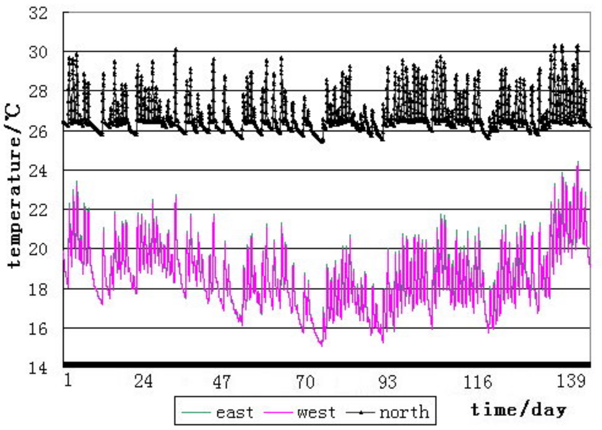

Fig.9a The inner surface temperature of wallboards in phase change greenhouse

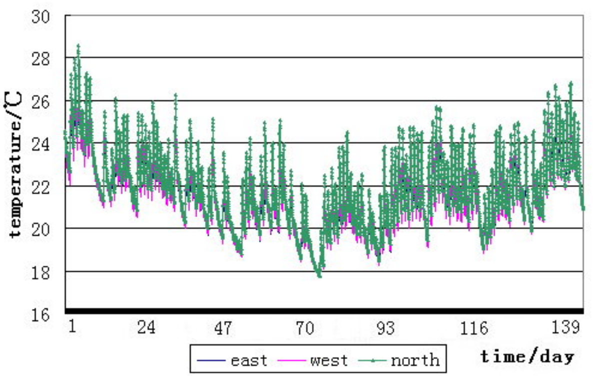

Fig.9b The inner surface temperature of wallboards in traditional greenhouse

From Fig 9a, b, it can be seen that the inner surface temperature of north wallboard, which is covered by a layer of composite PCM wallboard, is always above 25℃, average 7℃ higher than the east and the west wallboards during the whole winter. The minimum inner surface temperature of north wallboard is also controlled in the range of phase change temperature. After adding the PCM, two results come into being. On the one hand it will enhance the temperature of north wallboard and make the mean air temperature in the greenhouse rises 1℃ during the whole winter (Fig.10); On the other hand, though the thickness of the wallboard is reduced from 490mm to 240mm, the energy consumption doesn't increase, on the contrary having an obvious reduction. From the simulating results we can see that a traditional greenhouse needs 8.5-ton standard coal every winter, which is about equal to 12.1-ton original coal (the investigated data is 13-ton original coal); whereas the greenhouse with PCM wallboard only consumes 7.0-ton standard coal every winter, which is about equal to 10-ton original coal, the ratio of energy conservation is nearly 20%, and the energy saving effect of this new composite wallboard is obvious.

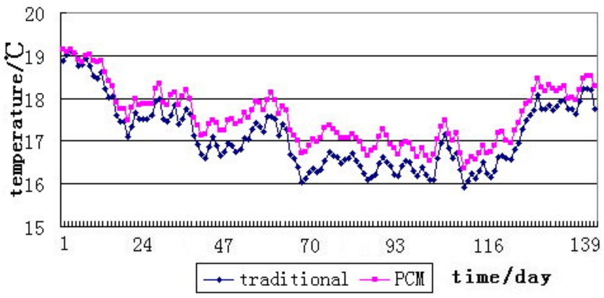

Fig.10 The variation of average air temperature in the whole winter

5. CONCLUSIONS

Making use of the thermal characters of PCM, large latent heat and heat storage, we can make light wallboard have the thermal characters of the heavy wallboard in some temperature range. If the PCM is used in the enclosure of greenhouse in north area, it could make full use of solar energy, and decrease the heat load in winter. Research results show that when phase change temperature of PCM is 26℃, the enthalpy is 60kJ/kg and the mix ratio is 40%, the energy saving rate of greenhouse can get to 20% during a whole winter.

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